Long Baseline Neutrino Physics: From Fermilab to Kamioka

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Fermilab

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- Motivation and goals

- Beamline design

- Results for $\sin^2(2\theta_{13})$ and δ

- Conclusions

Lab for LBL ?   overburden: 150m

Total Volume:
250K m³

Motivation and Goals

Ideas for a long-term JPARC-Kamioka program: $L = 295$ km
- Phase 1: 0.75 MW protons, 22.5 kton fiducial detector (Super-K)
- Phase 2: $\times 5$ proton power, $\times 20$ fiducial mass (Hyper-K)

Fermilab-Kamioka: $L = 9300$ km

- How can you observe a signal with such a long baseline?
  Matter effect $\Rightarrow \times 20$ amplification in S (over max in vacuum)
  $\qquad\qquad\qquad \times 20$ improvement in S/N

- How does it complement the JPARC beam?
  – May have best sensitivity to very small ν_e appearance.
  – Matter effects resolve hierarchy: Normal or inverted
  – Matter-amplified signal is mainly CP-conserving atmospheric component
  $\Rightarrow$ Use to separate CP-violating component seen with JPARC beam

Can we make a strong case for Phase 2 before $\sin^2(2\theta_{13})$ is known?
Yes, if sensitive to maximal CP violation for a wide range of parameters.
Goal: 3σ sensitivity to maximal CP violation for $\sin^2(2\theta_{13}) > 10^{-3}$.

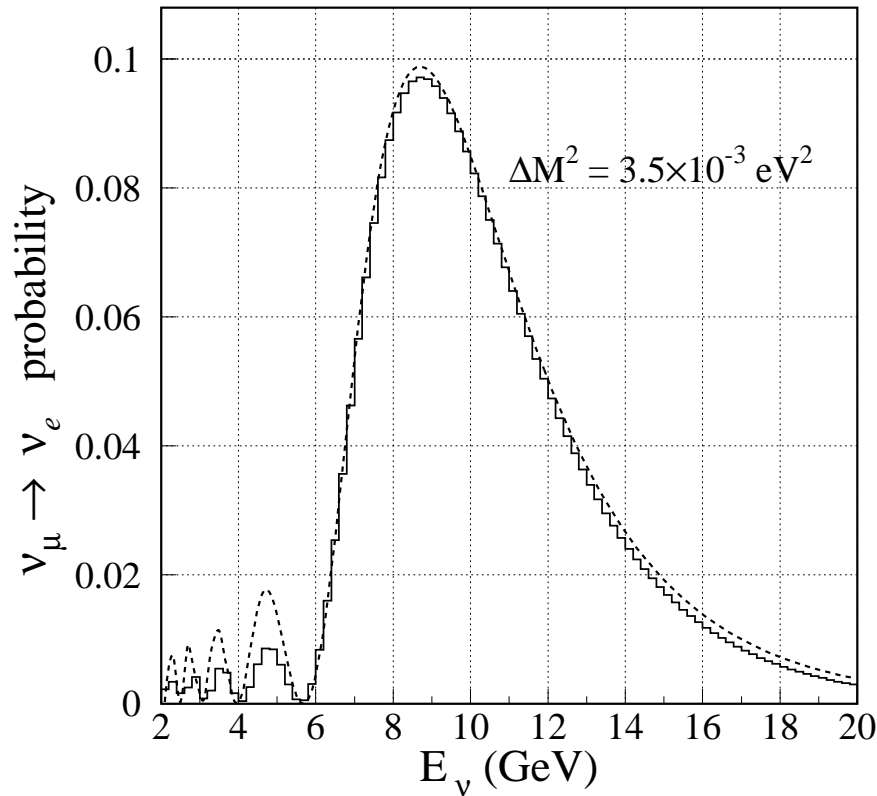# CP Asymmetry at the peak of the atmospheric oscillation
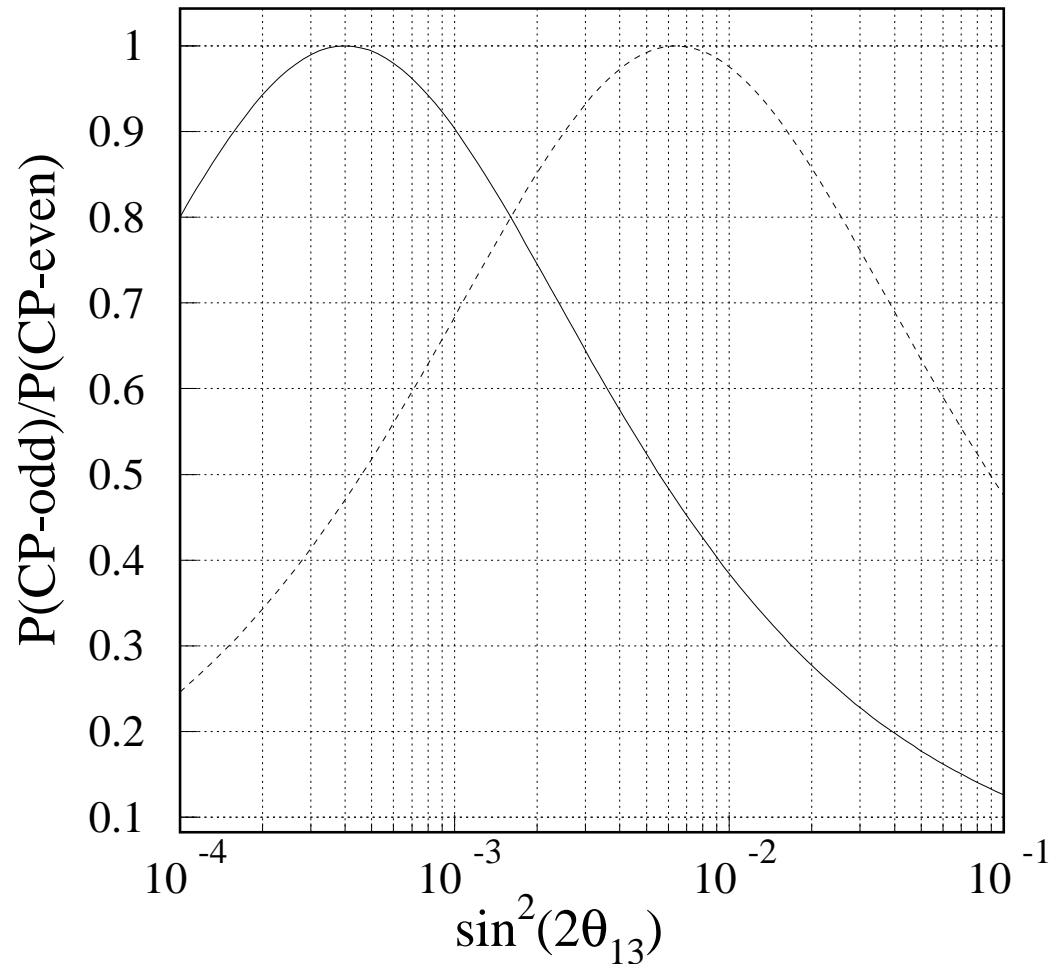
- Matter effects not included

- Solid line is for default parameters:

$\sin^2(2\theta_{13})$	variable
ΔM^2	3.5×10^{-3} eV^2
Δm^2	5.0×10^{-5} eV^2
$\sin^2(2\theta_{23})$	1.0
$\sin^2(2\theta_{12})$	0.8
δ	$\pi/2$

- Dashed line has $\Delta m^2 = 2 \times 10^{-4}$ eV^2

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Leading oscillations: $\bullet L = 9300$ km, $\bullet \sin^2(2\theta_{13}) = 0.01$

Solid: Numerical calculation.
Dashed: Analytical approximation,
with constant density.
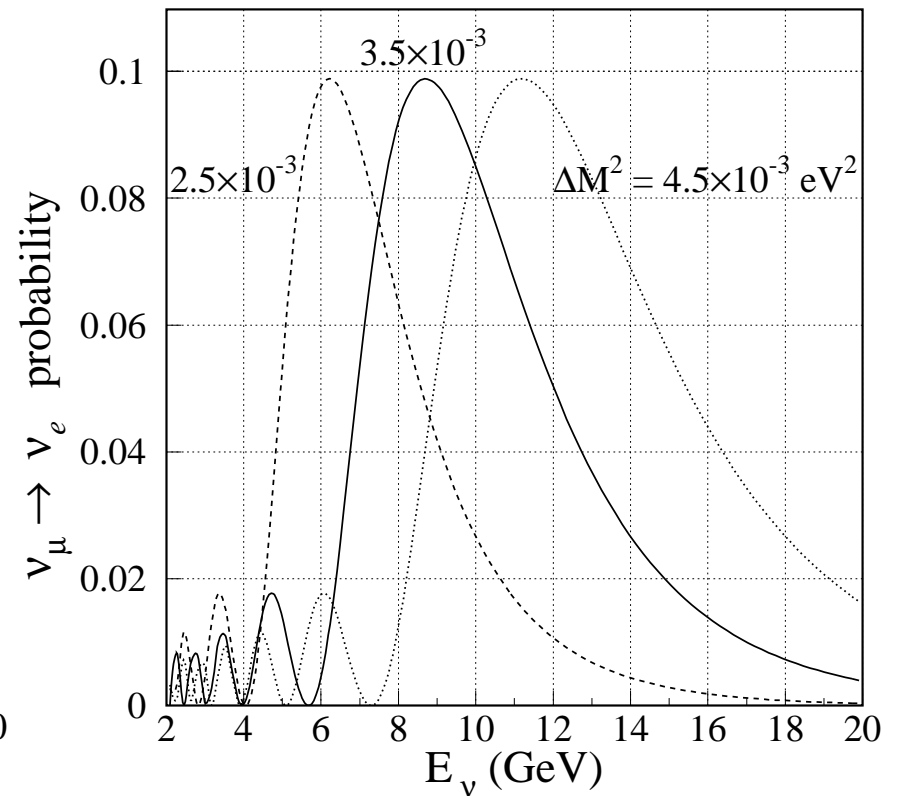
Dependence on ΔM^2

Beamline design

We start from the following observations:

1. Large matter effects occur at a particular resonant energy.
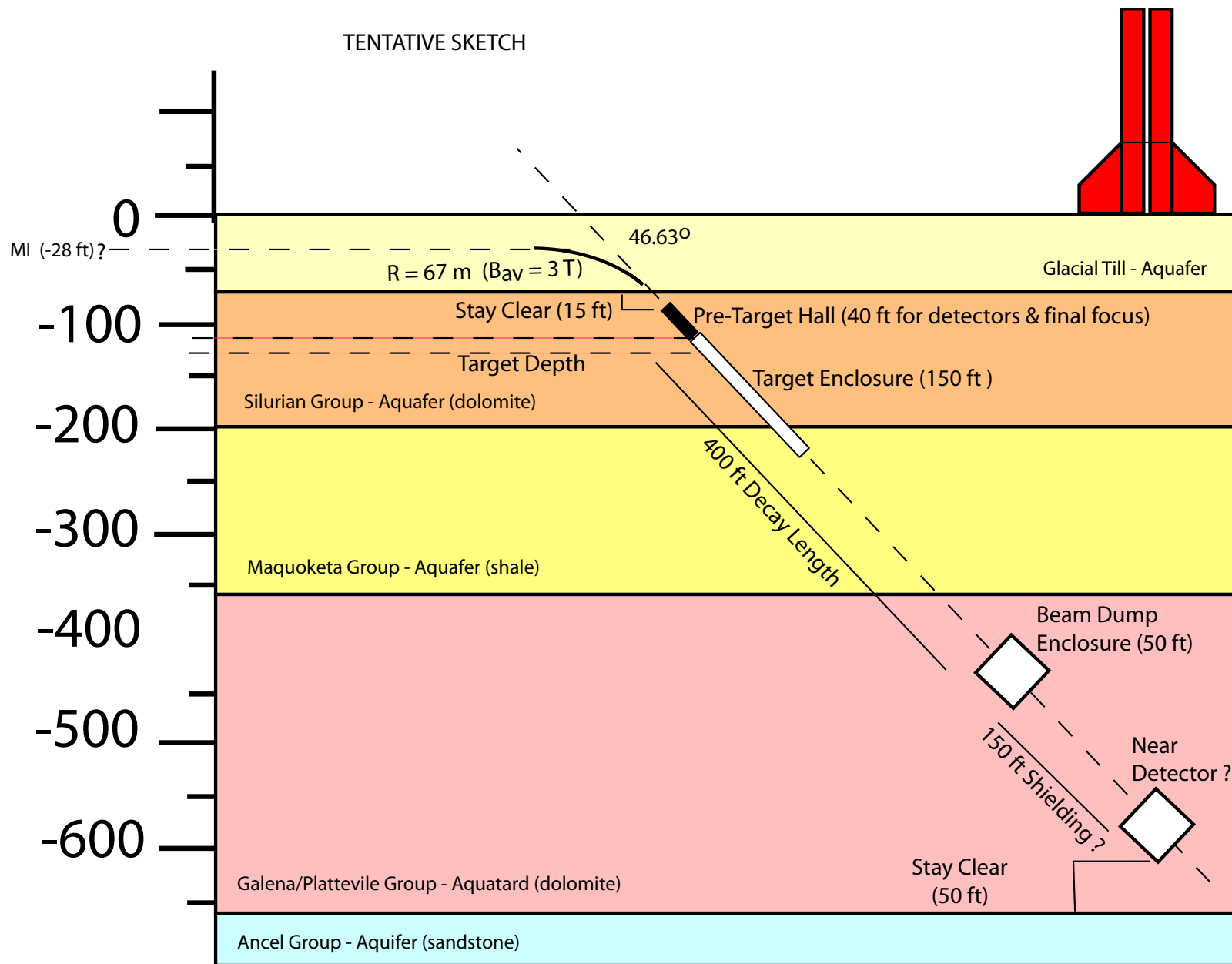2. Most backgrounds "feed-down" from E_ν to lower E_{vis}.

These lead to the following design principles:

1. Tune the spectrum to the resonant energy of the matter effect.
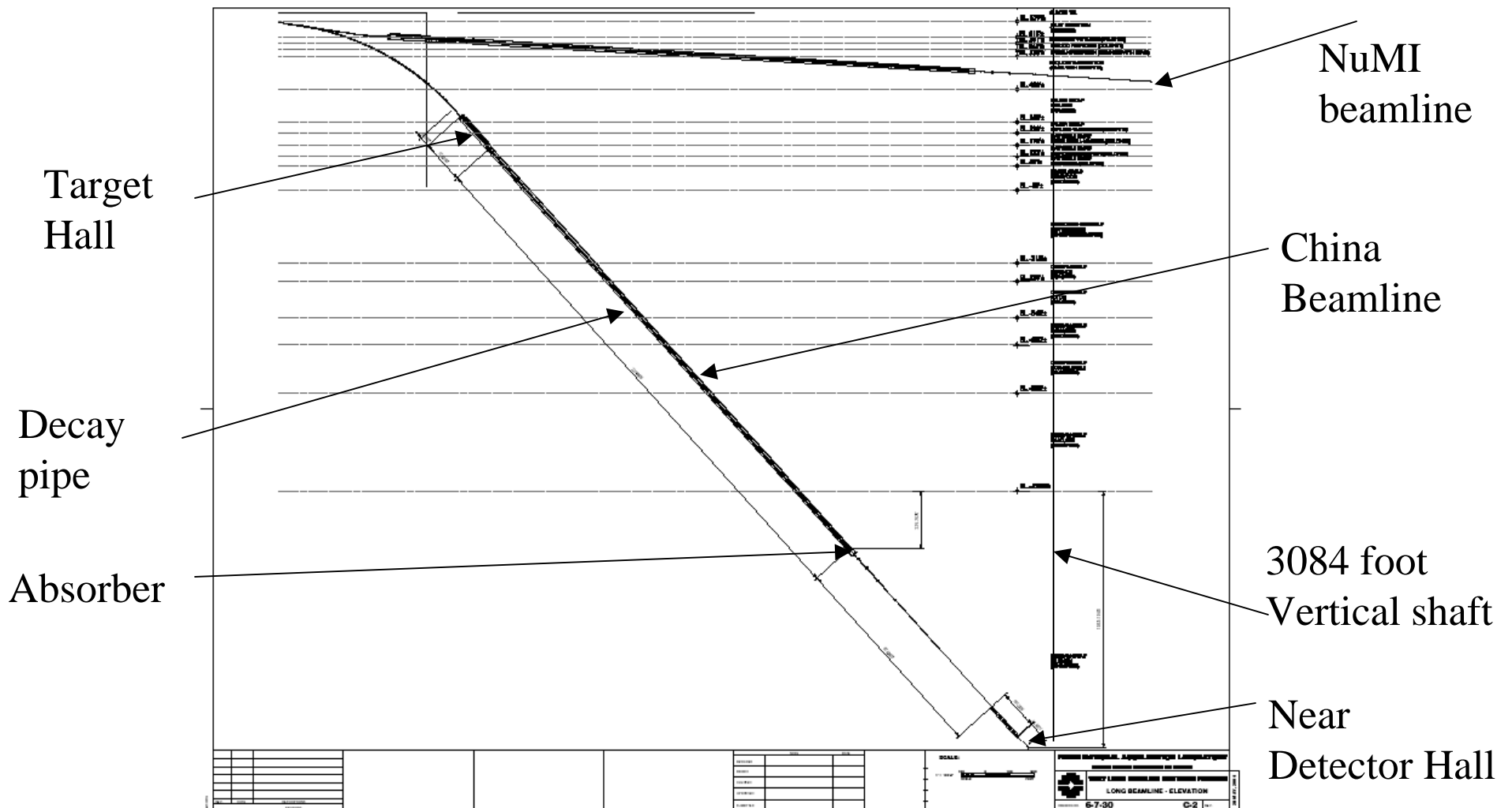2. Aim for a "sawtooth" spectrum shape, with sharp cut-off at high E.

We start with the NuMI design and make the following modifications:

1. 2 MW of proton power at 60 GeV (assumes linac proton driver)
2. Target/horn configuration producing peak in spectrum at 10 GeV.
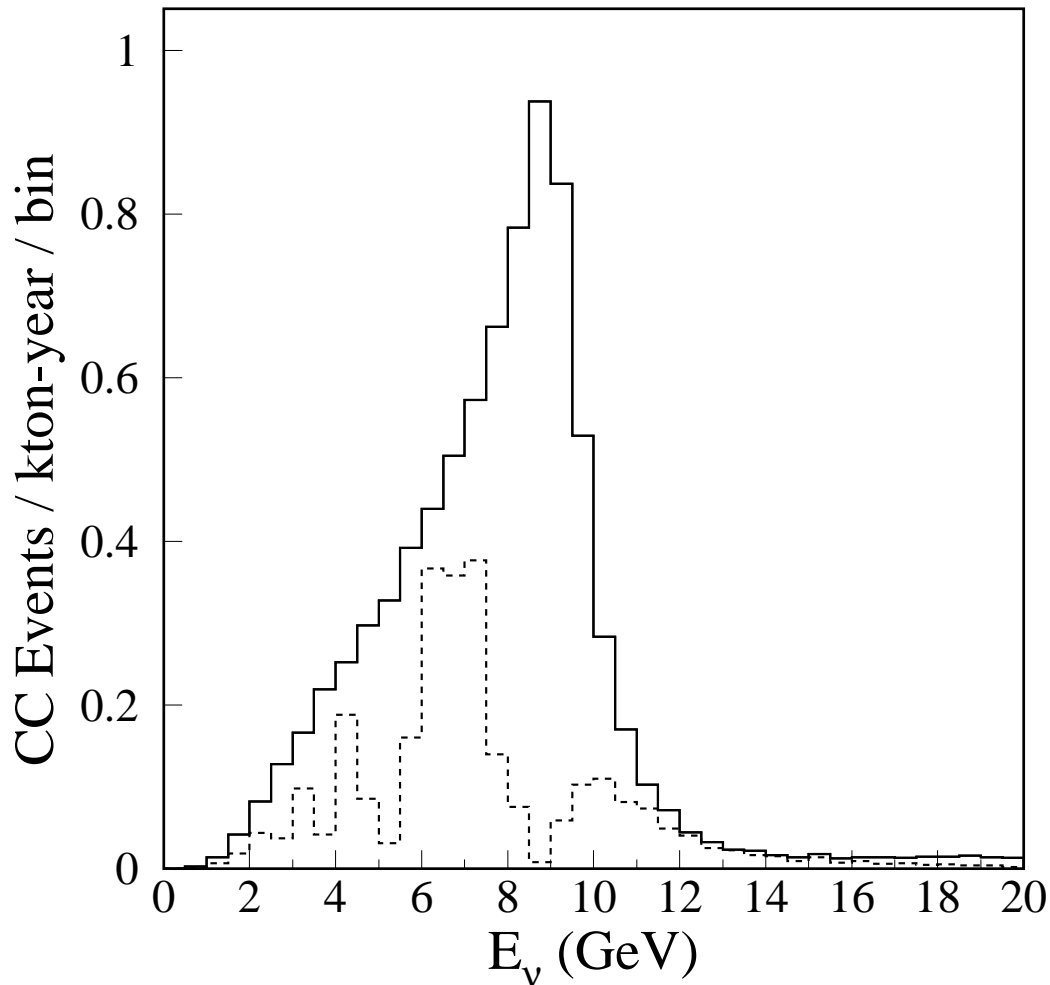3. Dipole bend after 2nd horn: 0.5° for 20 GeV pions.

Steve Geer has started work on the layout (nextpage).

TENTATIVE SKETCH

MI (-28 ft) ?

0

-100

-200

-300

-400

-500

-600

46.63°

R = 67 m (B$_{av}$ = 3 T)

Stay Clear (15 ft)

Pre-Target Hall (40 ft for detectors & final focus)

Target Depth

Target Enclosure (150 ft)

400 ft Decay Length

Glacial Till - Aquafer

Silurian Group - Aquafer (dolomite)

Maquoketa Group - Aquafer (shale)

Galena/Plattevile Group - Aquatard (dolomite)

Ancel Group - Aquifer (sandstone)

Beam Dump Enclosure (50 ft)

150 ft Shielding ?

Near Detector ?

Stay Clear (50 ft)

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China Baseline The "Elevation View" Sketch for Very Long Baseline Neutrino Project

NuMI beamline

Target Hall

China Beamline

Decay pipe

Absorber

3084 foot Vertical shaft

Near Detector Hall

Results from pbeam simulation

Solid line: ν_μ CC interactions assuming no oscillations.
Dashed line: With oscillations
2nd disappearance max occurs at peak!

The following factors are included:

- Scale up by 1.25 to agree with Geant results.

- Efficiency of tunnel is 37% relative to NuMI.

Signal selection: Find one EM ring with energy E

Solid: ν_e CC events.
Dash: $E > 4.5$ GeV, $E/E_{\text{vis}} > 0.45$
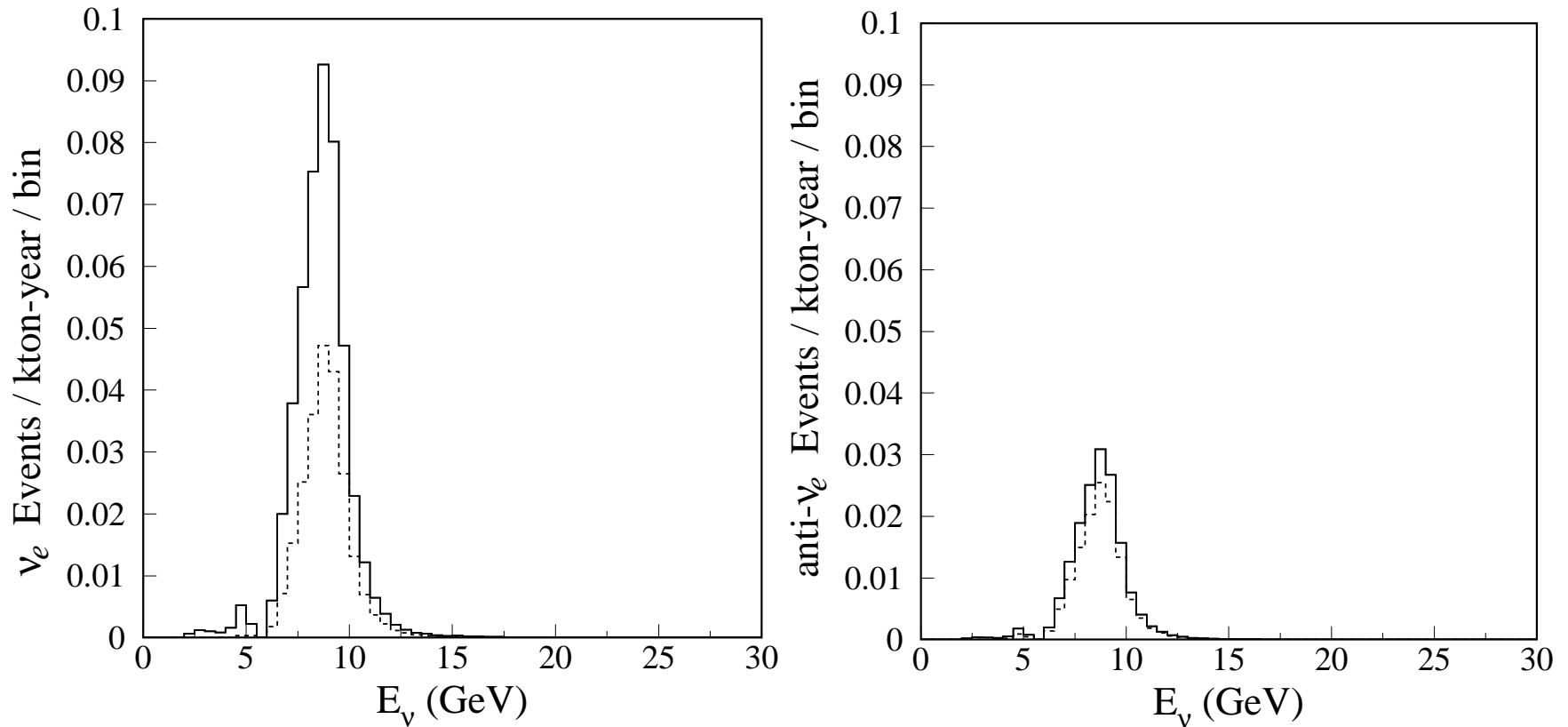
Solid: $\bar{\nu}_e$ CC events.
Dash: $E > 3.3$ GeV, $E/E_{\text{vis}} > 0.33$

After cuts, $\bar{\nu}_e$ rate $= 55\%$ of ν_e rate

Neutral-current background
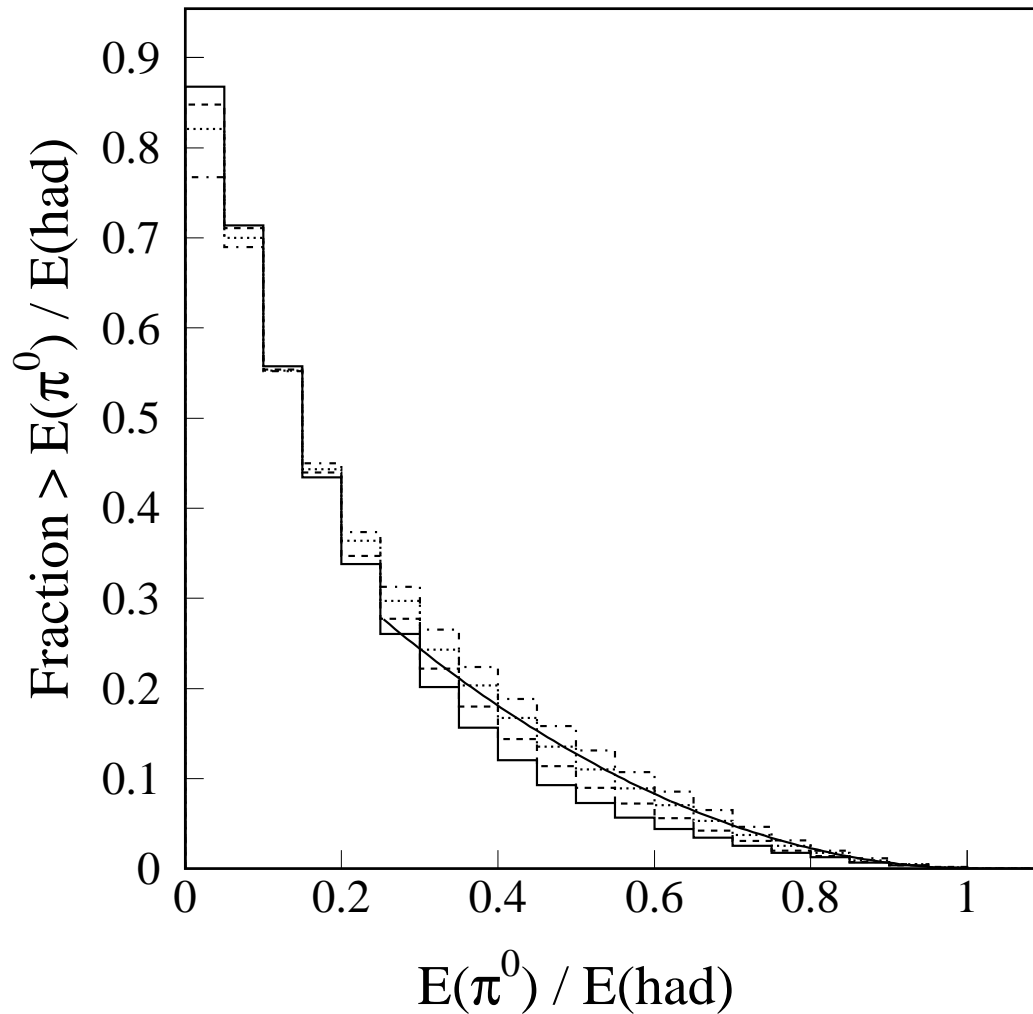
NC events with π^0 fragmentation are the major background

$\sigma_{NC} = 0.4 \ \sigma_{CC}$
Parametrize y distribution
Parametrize fragmentation
$\Rightarrow$ Convolute spectrum into NC background

Comparison of S and NC for $\sin^2(2\theta_{13}) = 0.01$ (leading)

Solid line: ν_e events
Dashed line: NC background
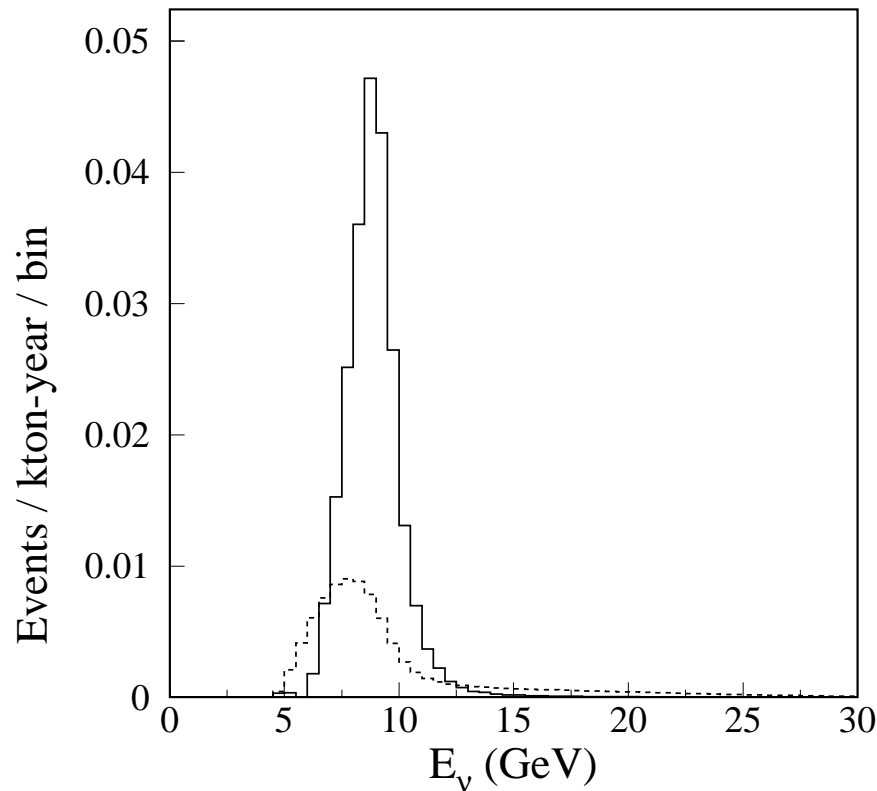
Solid line: $\bar{\nu}_e$ events
Dashed line: NC background

Neutrino direction information has not yet been used.

Other backgrounds

- ν_μ CC events. Reject events with a muon.
  Miss muon in high-y events.
  However, most ν_μ have disappeared.
  $\Rightarrow$ Assume negligeable.

- ν_τ CC events.
  Cross-section is 8% compared to ν_μ.
  $BR(\tau \rightarrow e\nu\bar{\nu}) = 18\%$.
  Missing energy $\Rightarrow$ Feeds down.
  Assume negligeable.

- Intrinsic ν_e
  Signal region is narrow part of spectrum.
  Dipole bend helps reduce source from neutral kaons.
  $\Rightarrow$ Should be very small.

Summary of signal and background rates

Normalized to $\sin^2(2\theta_{13}) = 0.01$ and leading terms only.

JPARC phase 1:

- $S = 0.11$ events/kton-year (0.55 in phase 2).

- $f_B = 0.51\%$

Fermilab:

- $S = 0.21$ events/kton-year

- $f_B = 2.5\%$
  $f_B = 0.13\%$ after scaling by matter amplification.

Reach in $\sin^2(2\theta_{13})$
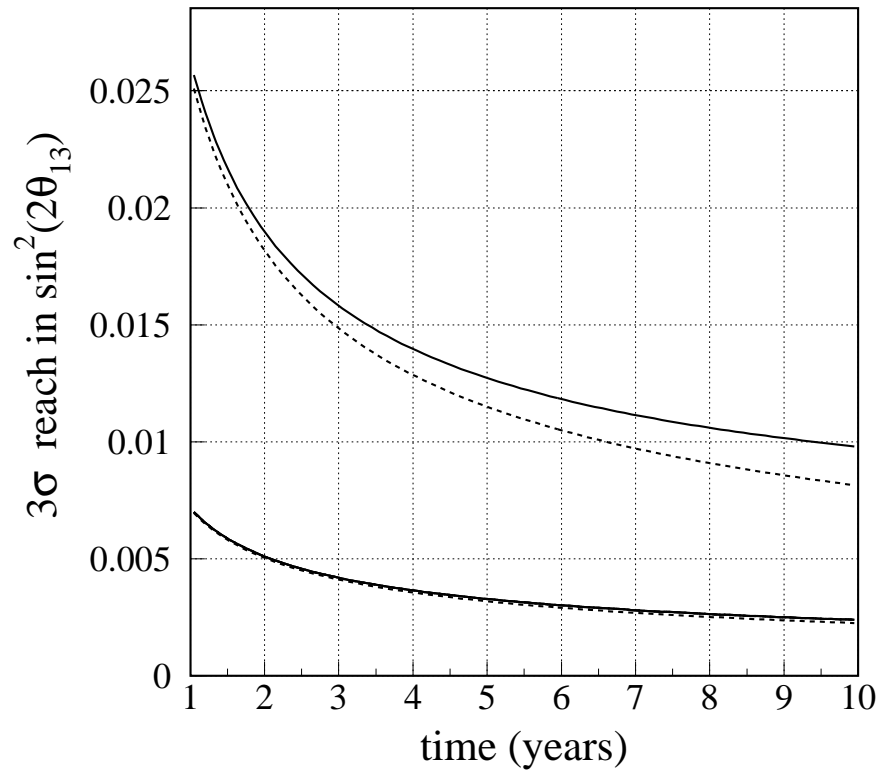
With Super-K detector.

With Hyper-K detector.

Upper curves: JPARC phase 1
Lower curves: Fermilab beam.
Solid curves: 10% systematic uncertainty on the background.
Dashed curves: no systematic uncertainty.
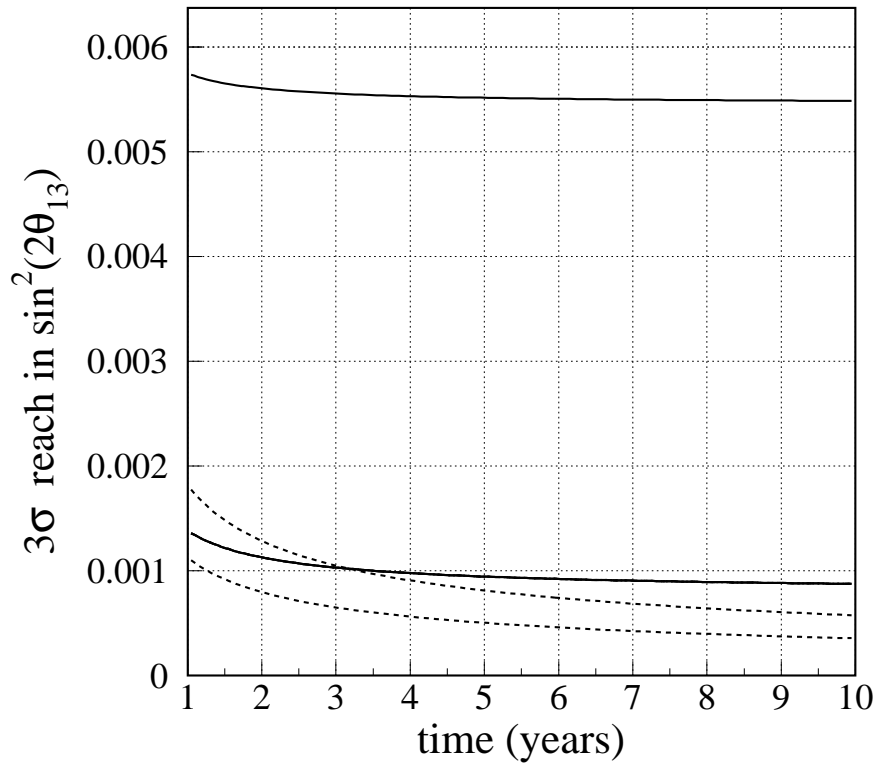
Constraints on CP violating phase with Hyper-K

We start with the following oscillation probability measurements which assume:
- Systematic uncertainty on B of 2% (JPARC) 5% (Fermilab).
- No flux uncertainty (it will need to be very well known for large $\sin^2(2\theta_{13})$).
- f_B same for ν and $\bar{\nu}$.
- 6 year JPARC $\bar{\nu}$ run equivalent to 2 year JPARC ν run.

Beam	ye-ars	$\sin^2(2\theta_{13})$		
		0.01	0.05	0.001
Fermi	2	0.104 ± 0.0060	0.501 ± 0.012	0.012 ± 0.0034
Fermi	8	0.104 ± 0.0032	0.501 ± 0.0061	0.012 ± 0.0021
JPARC ν	2	$(7.9 \pm 0.37) \cdot 10^{-3}$	$(3.2 \pm 0.052) \cdot 10^{-2}$	$(1.5 \pm 0.32) \cdot 10^{-3}$
JPARC ν	8	$(7.9 \pm 0.25) \cdot 10^{-3}$	$(3.2 \pm 0.031) \cdot 10^{-2}$	$(1.5 \pm 0.24) \cdot 10^{-3}$
JPARC $\bar{\nu}$	6	$(2.8 \pm 0.33) \cdot 10^{-3}$	$(1.8 \pm 0.044) \cdot 10^{-2}$	$(0.0 \pm 0.31) \cdot 10^{-3}$

$\Rightarrow \chi^2$ constraints in $\sin^2(2\theta_{13}) - \delta$ plane
(uncertainties on other parameters not yet included)

2 years with Fermilab beam.

8 years with Fermilab beam.

2 years with JHF beam.

6 years with JHF anti-neutrino beam.

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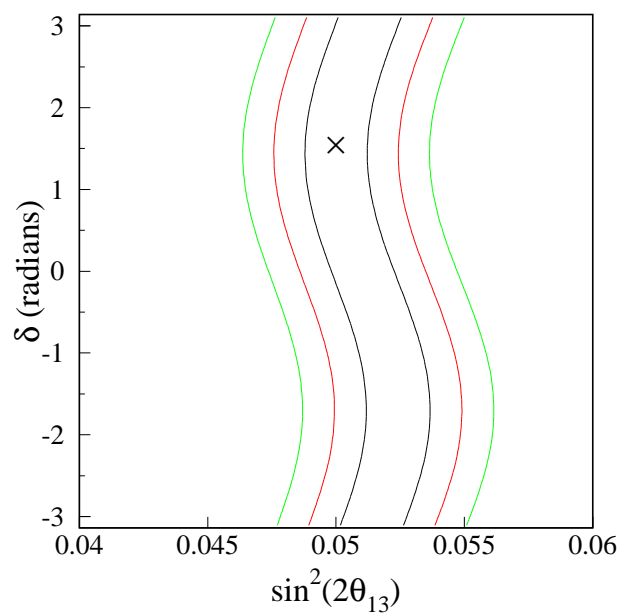2 years
with
Fermilab
2 years
with JHF

8 years
with
Fermilab
8 years
with JHF

2 years
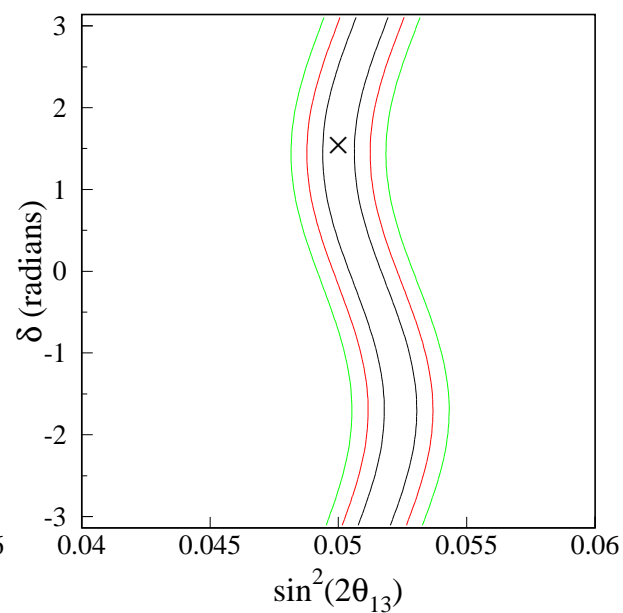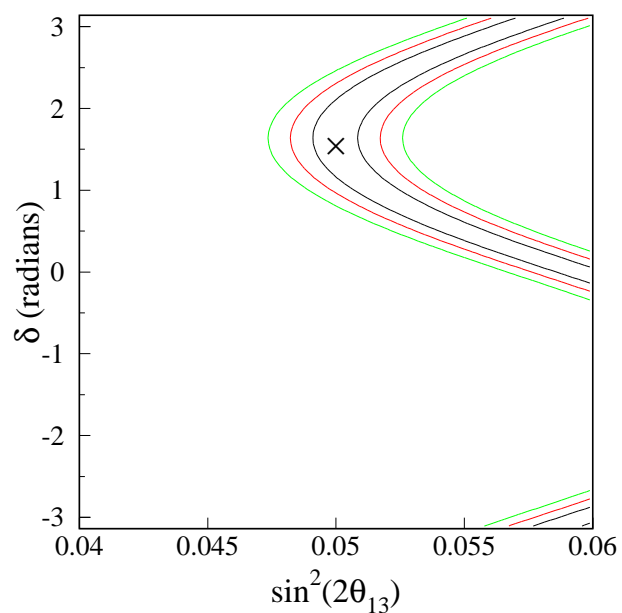with JHF
6 years
with JHF
anti-
neutrino

8 years
with
Fermilab
2 years
with JHF
6 years
with JHF
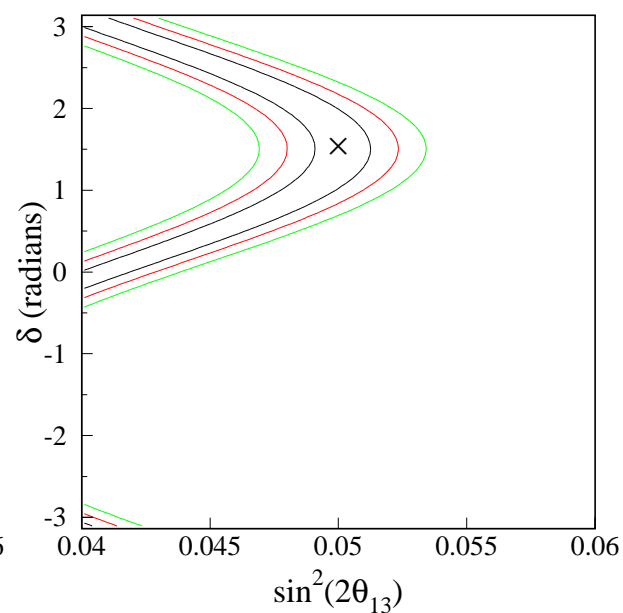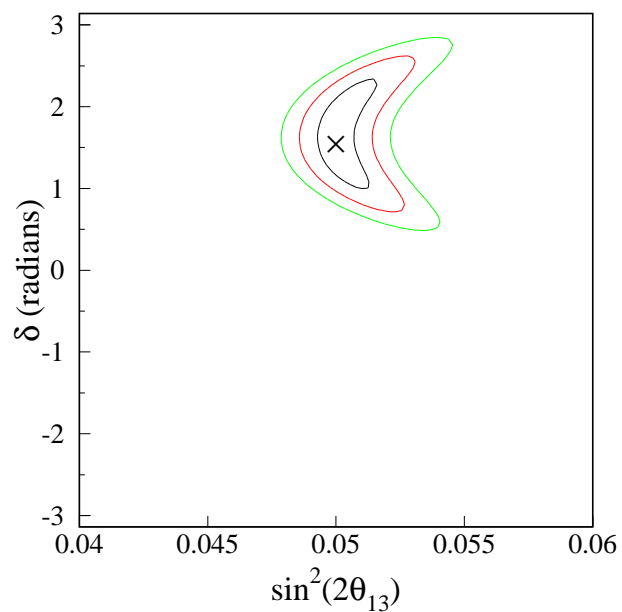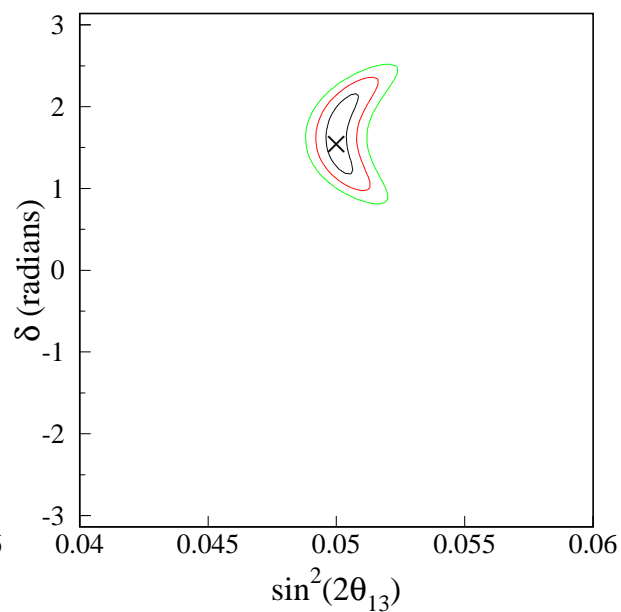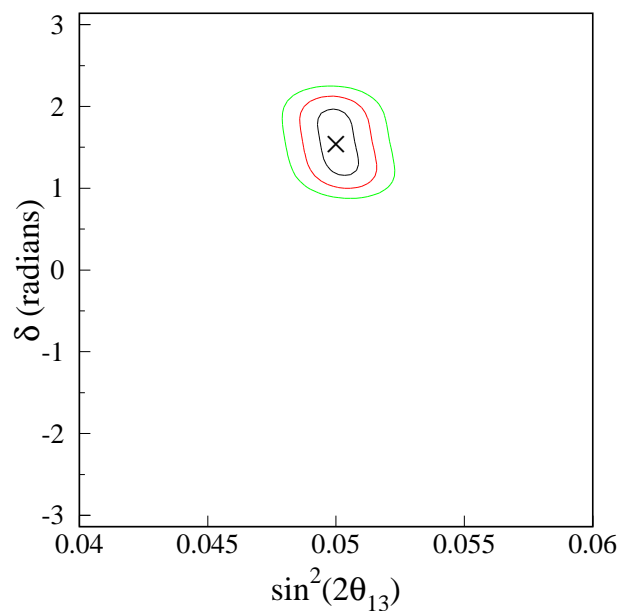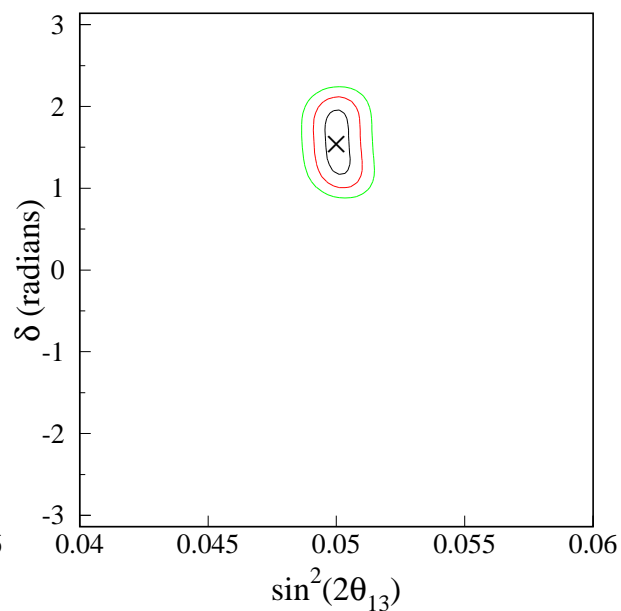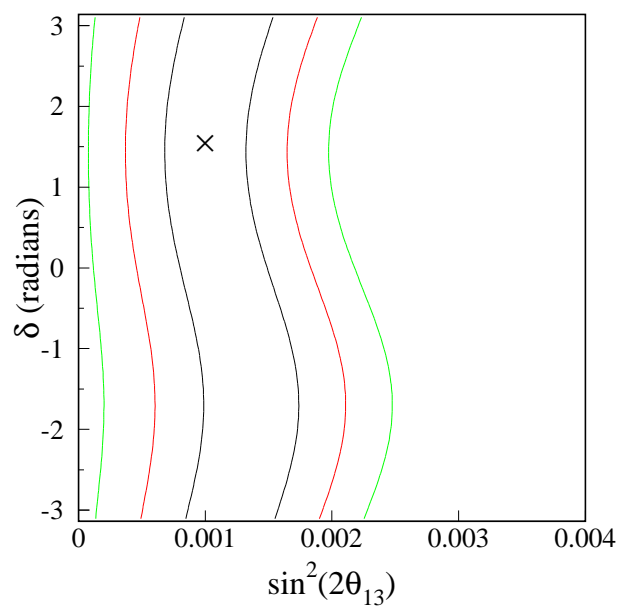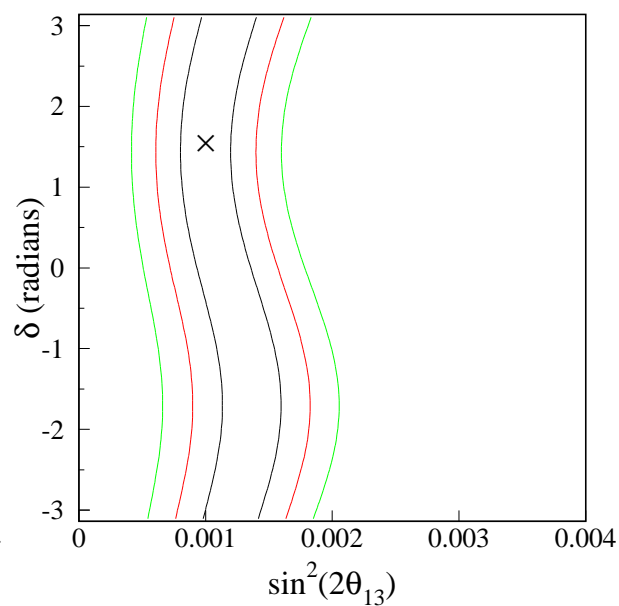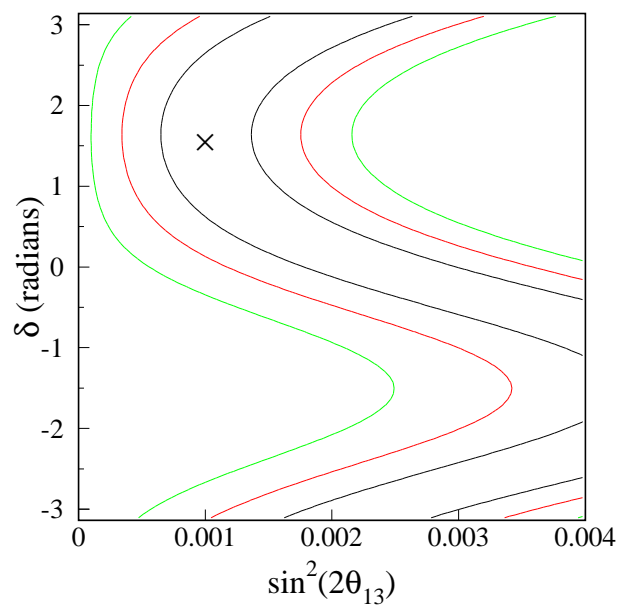anti-
neutrino
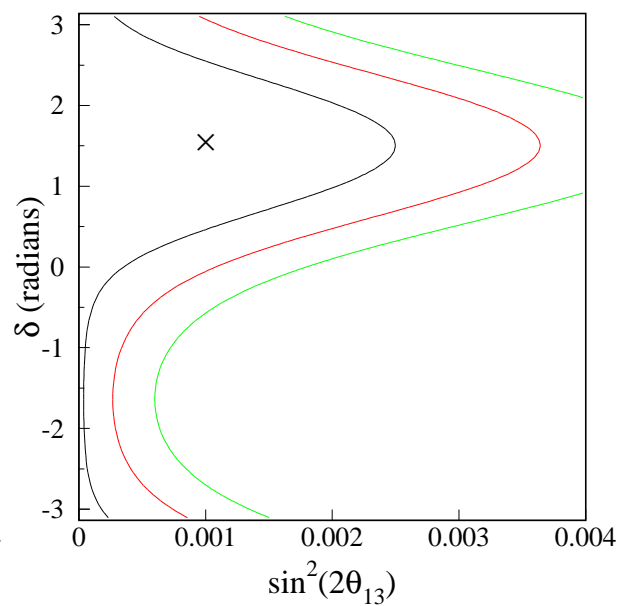
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2 years
with
Fermilab
beam.
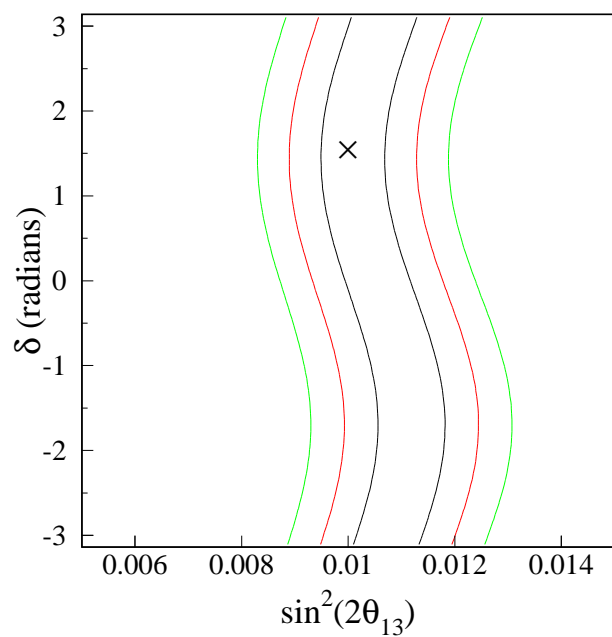
8 years
with
Fermilab
beam.
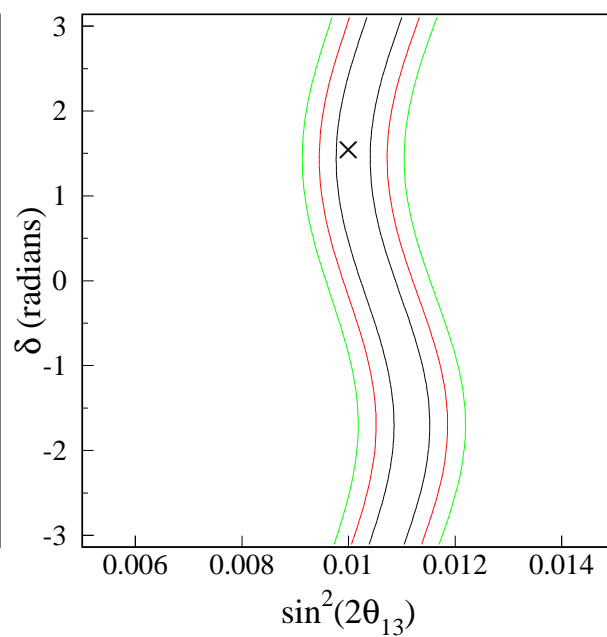
2 years
with JHF
beam.
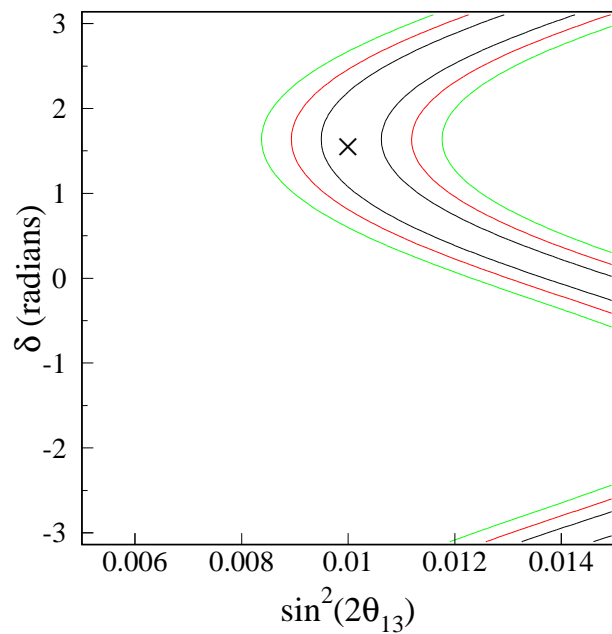
6 years
with JHF
anti-
neutrino
beam.

2 years
with
Fermilab
2 years
with JHF

8 years
with
Fermilab
8 years
with JHF

2 years
with JHF
6 years
with JHF
anti-
neutrino

8 years
with
Fermilab
2 years
with JHF
6 years
with JHF
anti-
neutrino

δ (radians)

$\sin^2(2\theta_{13})$

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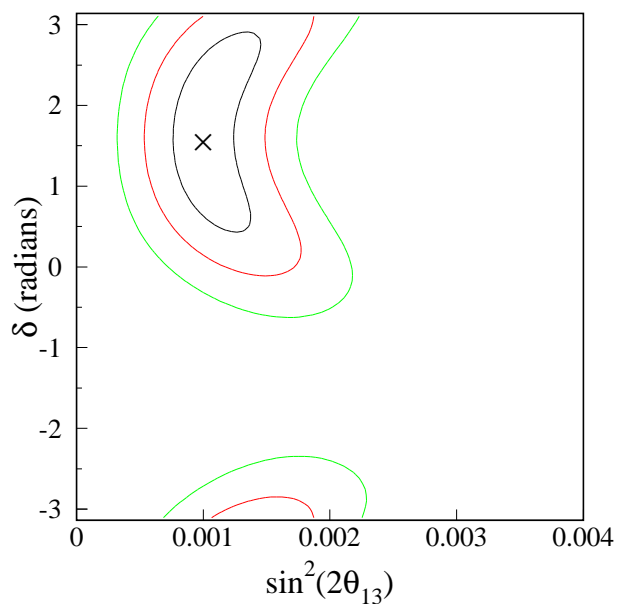
2 years with Fermilab beam.

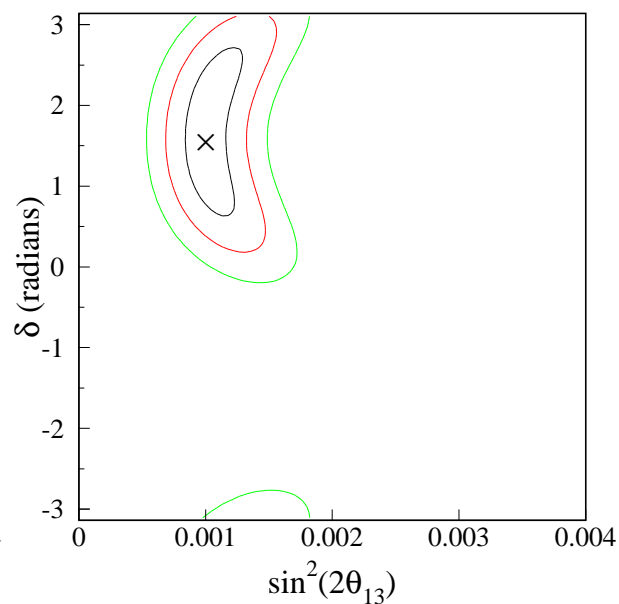8 years with Fermilab beam.

2 years with JHF beam.
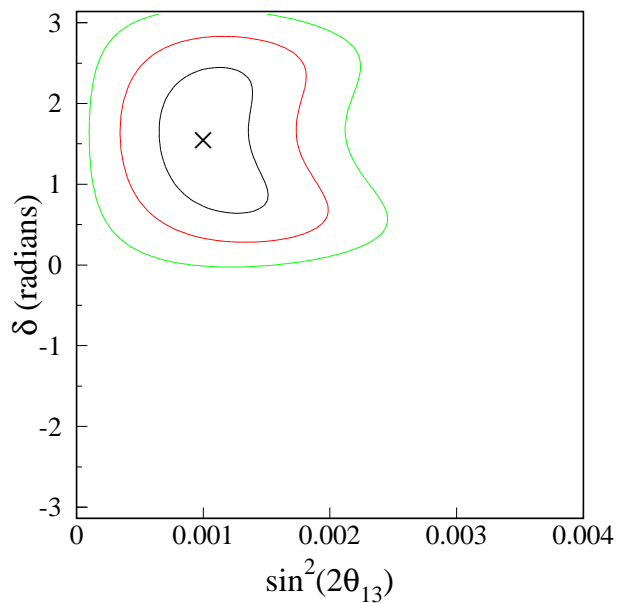
6 years with JHF anti-neutrino beam.
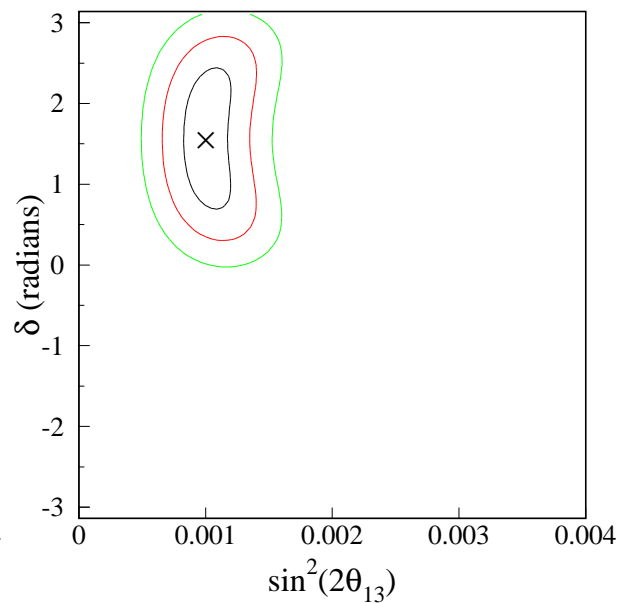
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2 years
with
Fermilab
2 years
with JHF

8 years
with
Fermilab
8 years
with JHF

2 years
with JHF
6 years
with JHF
anti-
neutrino

8 years
with
Fermilab
2 years
with JHF
6 years
with JHF
anti-
neutrino

Conclusions

Very long baseline experiments are potentially very useful, depending on:

- Size of $\sin^2(2\theta_{13})$

- Location of world's largest detectors and most intense neutrino sources

- Readiness of neutrino factory